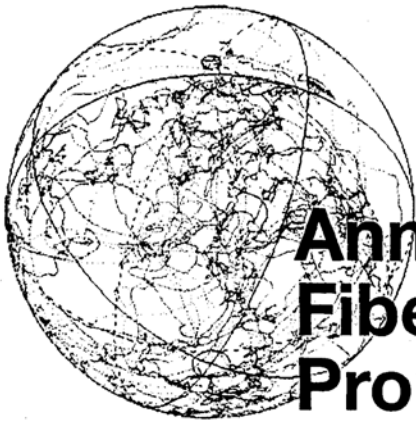


Annealing Optical Fiber: Applications and Properties

A.H. Rose
NIST Optoelectronics Div.
Boulder, CO

Annealing optical fiber, if done properly, can produce useful fiber components.

Annealing a fiber involves raising the glass to a temperature above the strain point for a short time and slowly cooling back to room temperature. This process not only reduces stress in the glass, but also initiates a number of physical and chemical changes to the glass.

Current Sensing

The annealed fiber coil is an essential component of optical fiber current sensors, or optical current transducers (OCT). OCTs have several economic and performance advantages over conventional current transducers in fault detection and metering.

The bandwidth and high dynamic range of these sensors provide the power utility engineer with a diagnostic tool for evaluating the behavior of generators and the transmission grid. Because of their all-dielectric design, installation costs are significantly lower and sensor failure does not pose a threat to power utility personnel or equipment.[1]

The two most common OCTs are the polarimetric design and the Sagnac interferometric design. In a polarimetric OCT, the polarizer and analyzer are oriented to convert a rotation of the polarization state into an intensity change at the photodetectors.

The Faraday effect provides a rotation of the light's electric field orientation, or polarization state, when a magnetic field is parallel to the optical path in a glass. If the light path is closed around a conductor, or nearly so with an optical fiber, Ampere's law applies, and the Faraday rotation is directly proportional to the current flowing through the aperture of the closed path.

Thus, an optical fiber coil can be used to make a true optical current sensor and not just a magnetic field sensor near a current-carrying line. (Magnetic field sensors have low isolation to nearby currents and/or magnetic fields.) The closed optical path of the OCT also increases the device's isolation to nearby currents or magnetic fields.

The Sagnac sensor interferometer current sensor also can measure the Faraday rotation. Two counter-propagating light beams in the Sagnac sensor interfere at a coupler. When the two beams experience a phase shift due to an optical path change from current flow, an intensity change at the coupler is proportional to the current flowing through the aperture. The current is measured by monitoring the control-circuit output.[2]

The simple polarimetric current sensor has a high bandwidth and no saturation. It is best suited for fault detection and pulse current metrology. Polarimetric current sensors have been used successfully to measure current pulses of >10 MA with ~1% accuracy.

The more complex heterodyned Sagnac current sensor has excellent stability and is best for DC and current metering.

The subtleties of making a practical device with a fiber coil are related to the nature of the Faraday effect and detecting a change in the polarization state of light (polarimetric detection) or phase shift (interferometric detection_. A linear state of polarization rotates in the presence of a magnetic field because the field produces a circular birefringence in the glass. (Birefringence refers to an optical material with two indices of refraction.)

Thus, right and left circularly polarized light will travel at different speeds and accumulate a relative phase difference. A linear state of polarization can be modeled as the superposition of two equal intensity, right and left circular polarization states. As the linear state propagates through a glass with circular birefringence, the accumulated phase difference rotates the linear state.

Another type of birefringence that is easy to produce in glass is linear birefringence. In a linearly birefringent glass, horizontally and vertically polarized light propagates at different speeds, and again, accumulates a phase difference.

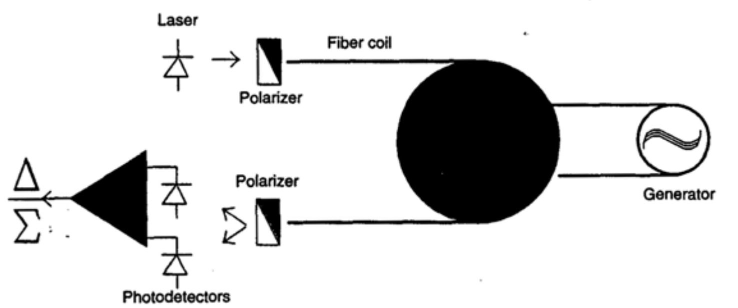
However, the phase difference changes the polarization from linear to some elliptical state. In polarimetric detection, linear and circular birefringence are not always distinguishable, and linear birefringence can easily swamp the effects of circular birefringence.

Linear birefringence also has a large temperature dependence, which destabilizes the sensor. Thus, to measure the weak Faraday effect in optical fiber and make a practical current sensor, the linear birefringence must be removed from the fiber.[1]

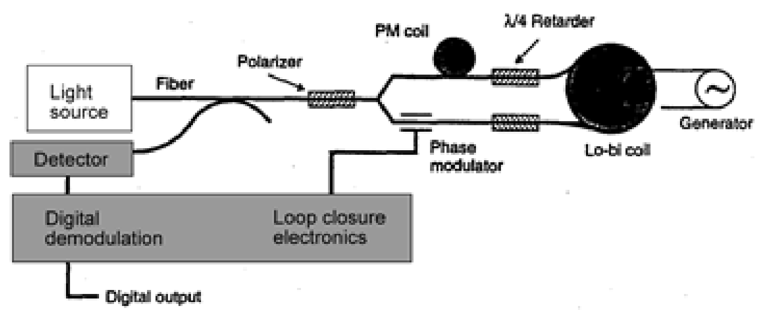
Linear birefringence in fiber arises from stress, applied externally (ending_ or internally (drawing process and fiber structure), and from waveguide shape (a noncircular core). Annealing the fiber will relieve all stress-induced linear birefringence.

The waveguide-induced linear birefringence cannot be removed, but its effects can be significantly reduced by twisting the fiber. If the twist rate is about twice the amount of accumulated phase in a given length of fiber, the effects of linear birefringence will be greatly reduced.

The combination of twisting and annealing the fiber increases the current sensitivity of an annealed fiber coil to nearly that of an isotropic, or perfect, fiber.[3] At present, several universities and companies are exploring the application and production of annealed-fiber OCTs.



Schematic of a polarimetric OCT. The two photodetector outputs are summed, Σ, and the difference, Δ, taken. The quotient output of the difference divided by the sum, Δ/Σ, removes common mode noise.



Schematic of a Sagnac OCT. Polarization maintaining(PM) fiber and low-birefringence (Lo-bi) fiber are used to prepare and preserve the needed polarization states for current measurement.

Detrimental Effects

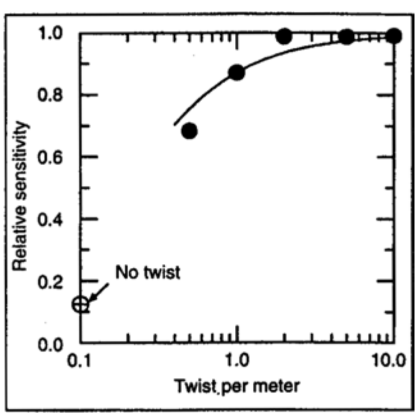
Annealing glass can, under certain conditions, produce undesirable effects in fiber. These effects are: increased OH concentration in the glass and devitrification (i.e., the nucleation and growth of crystals within the glass).

Our fiber annealing is done in an air environment with the acrylate jacket in place. At temperatures between 500-600ºC, the jacket burns away.

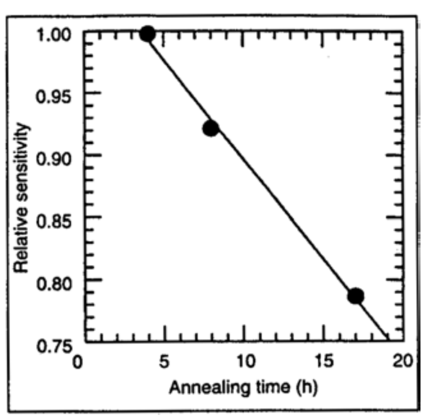
The jacket is treated before the annealing cycle with acetone, which causes the jacket to sell. The acetone-treated jacket does not hold the glass tightly, so minimum damage to the glass surface occurs during the jacket combustion.

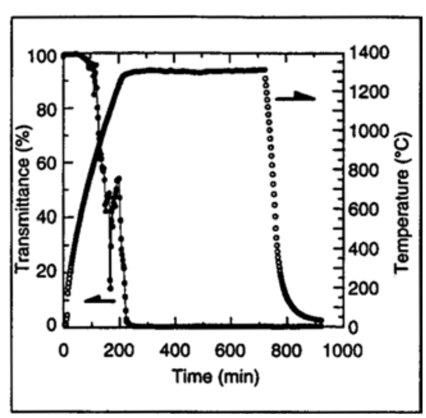
As the jacket burns, it expands, stressing the fiber coil. With careful winding techniques, however, the fiber coil can survive this stress.

When the jacket burns during annealing, many chemical reactions occur, but the primary species formed is water. At annealing temperatures, water reacts with the glass surface to form OH. OH reduces the strength of the glass and will cause loss at absorption bands around 1390 nm.



The relative sensitivity vs. twist per meter for 7 cm diameter, 20.9 turn fiber sensor coils.





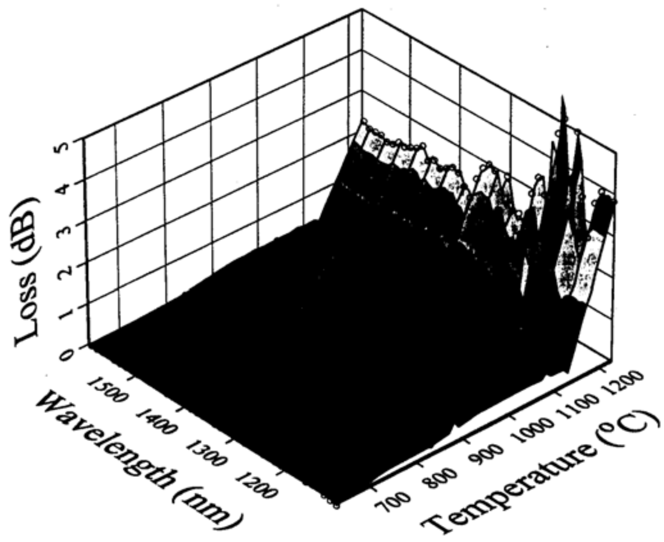
The transmittance and thermal history of a fiber annealed at ~1310ºC for 8 h. The o's mark the temperature and the •'s mark the transmittance.

Ambient air annealing also allows water in the air to react with the fiber surface to again produce OH. At temperatures ~850ºC, the OH reaction is slow, and significant concentrations of OH take >50h to reach the core region of the fiber.

At higher temperatures, ~1000ºC, the reaction accelerates, and OH can reach the core in only a few hours. Above 1000ºC, however, the reaction reverses. The glass dehydroxylates, and OH is removed from the glass. The OH and water in the glass also aid in devitrification.[4]

Devitrification in silica can occur through nucleation and crystal growth at temperatures between ~200ºC-800ºC, depending on the glass composition. From the nuclei present, crystal growth continues for temperatures near 800ºC to a few hundred degrees below the melting point (~1800ºC in fibers).

If the temperature of the glass remains low, nucleation and crystal growth will occur at a negligible rate. Further thermal processing into the crystal growth temperature range, however, will promote the growth of the nuclei into larger crystals.



Optical loss of an annealed fiber vs. wavelength and temperature. The surface was interpolated from the data shown above as dots.

Devitrification usually starts at the glass-air surface and proceeds inward. This can be due to the presence of surface flaws or due to chemical reaction with water from the air or jacket combustion. At annealing temperatures >1000ºC and heating rates ~5ºC/min, crystal growth is rapid and starts primarily at the surface, propagating into the fiber core.[5]

Devitrification of the fiber increases scattering loss, depolarizes the light and reduces the strength of the fiber. For our typical annealing cycle (heating at ~5ºC/min to 850ºC, dwell for 4 h and then cooling at 0.2ºC/min to room temperature), the effect of devitrification is small. Longer annealing times can produce enough depolarization to reduce the current sensitivity of a fiber coil.

For higher annealing temperatures, >1000ºC, and times <10 h, losses in annealed fiber can be due to scattering, fiber fracture and possible stress-induced microbending from surface crystal growth. At these high temperatures, optical loss and fiber fragility increase, making current sensing with this type of fiber impractical.

For fiber heated to temperatures > 1200ºC, the OH concentration in the fiber moves rapidly to the core and is seen as an absorption at a wavelength of ~1390 nm. The small peak at 1390 nm and 950ºC is associated with the absorption of OH.

However, as the fiber is heated beyond 1000ºC, the OH concentration decreases due to the OH reaction reversal. At temperatures >1200ºC, the crystal growth produces broadband loss in the fiber.

Crystal growth at the surface is greatly affected by the treatment and type of jacket on the annealed fiber. As the jacket burns, the surface of the glass is altered to promote crystal growth through chemical attack.

For fiber that endures fire or other high-temperature processing, the jacket material becomes critical to fiber survivability and loss. Silica fiber sensors of any kind are not practical for long-term use >1000ºC.

Fiber Depolarizer

The crystal growth in heat-treated fibers can be used to make a depolarizing fiber. For optical systems that measure the polarization-dependent loss of a component, the detector must be insensitive to the polarization-state.

With the proper heat treatment, an annealed multimode fiber can be made to depolarize or scramble the polarization state of the light passing through it to the photodetector.

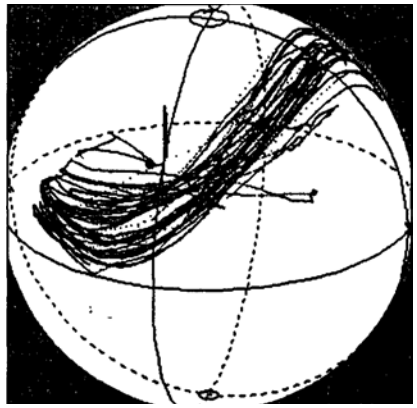
Both unannealed and annealed fibers have similar depolarization effects; reducing a 30% degree of polarization on the input to 1.5% at the output of the fiber. The annealed fiber, however, accomplishes this depolarization with a much shorter length of fiber, and the polarization-state motion is random.

Increased Photosensitivity

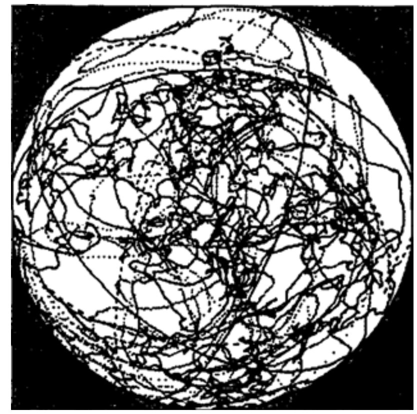
Fiber Bragg gratings (FBG) are a basic optical filter in fiber telecommunication systems. An FBG written in a fiber can reflect or block a wavelength band of light passing through the fiber. An FBG also can correct for dispersion in fiber systems and is an excellent strain sensor.

FBGs are made by exposing a fiber to a periodic pattern of UV light. This produces an index modulation in the fiber. The period and depth of the index modulation and modulation profile determine the optical characteristics (center wavelength, bandwidth, reflectance, etc.) of the FBG.

Oven annealing fibers >1000ºC increases the photosensitivity of a fiber to UV, so shorter exposure times and larger index changes can be achieved. UV photosensitivity arises from defects in the glass matrix. Annealing a fiber >1000ºC forms crystal defect sites in the fiber for increased photosensitivity.[6]



Poincaré sphere showing the polarization motion with a 45 m unannealed multimode fiber.



Poincaré sphere showing the polarization state motion of a 1 m multimode fiber annealed for 8 h at 950ºC.

Conclusion

Annealing optical fibers has made the optical fiber current sensor practical for monitoring and diagnostics done by utility companies. To produce an annealed-fiber coil for this application, the annealing process must be held within time and temperature bounds, or devitrification and OH absorption will degrade coil performance.

Annealed-fiber devitrification can produce other useful fiber components. These include a fiber depolarizer and increased photosensitivity for FBG production.

References

[1] G.W. Day, K.B. Rochford and A.H. Rose, "Fundamentals and Problems of Fiber Current Sensors"; pp. 124-29 in *Proceedings of OFS-11*, Sapporo Japan, May 1996.

[2] S.X. Short, A.A. Tselikov, J.U. de Arruda and J.N. Blake, "Imperfect Quarter-Waveplate Compensation in Sagnac Interferometer-Type Current Sensors," *J. Lightwave Technol*., **16** 1212-19 (1998).

[3] A.H. Rose, Z.B. Ren and G.W. Day, "Twisting and Annealing Optical Fiber for Current Sensors," *J. Lightwave Technol*., **14** 2492-98 (1996).

[4] A.H. Rose and T.J. Bruno, "The Observation of OH in Annealed Optical Fiber," *J. Non-Cryst. Solids*, **231** 280-85 (1998).

[5] A.H. Rose, "Devitrification Effects in Annealed Optical Fiber," *J. Lightwave Technol*., **15** 808-14 (1997).

[6] R. Kashyap, *Fiber Bragg Gratings*, Academic Press, San Diego, Calif., 1999.